Available Online: 10 October 2026 DOI: 10.54254/2977-3903/2026.37562

A review of the development, research progress and key challenges in underwater bionic soft robotics

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Abstract. Conventional rigid underwater robots possess high structural stiffness and exhibit a single mode of locomotion, showing poor adaptability in complex flow fields, narrow spaces and eco-friendly underwater operations. In recent years, underwater bionic soft robots have achieved rapid development boasting a rich variety of bionic prototypes as well as innovative actuation and control strategies. Nevertheless, most existing reviews focus on individual technologies, and few systematically integrate technological evolution, state-of-the-art progress and technical bottlenecks. Adopting a literature review approach, this paper investigates representative domestic and foreign papers and prototypes in the past decade. Through classification, comparison and induction, it sorts out the development history and summarizes mainstream technical systems of bionic structures, flexible actuation and sensing-control systems. The results reveal that this field has experienced three phases: exploration of rigid bionic prototypes, development of fully soft-bodied robots. However, difficulties in fluid-solid coupling dynamic modeling, limited underwater sensing accuracy, high actuation power consumption and poor adaptability to complex sea conditions remain major obstacles to practical deployment.This paper can provide references for further research tailored to practical nearshore tasks including coral-reef ecological survey, coastal organism-behavior observation, narrow-reef-crevice hazard inspection and man-made underwater-facility patrol of underwater bionic soft robots.

Keywords: soft robotics, underwater bionic robot, driving mechanism, technology development, underwater perception

1. Introduction

Traditional rigid underwater robots are widely deployed for marine exploration, rescue missions and underwater-facility inspection. Nevertheless, when these robots operate in complex, narrow reef-congested waters, their rigid structures are susceptible to collision-induced damage. They also exhibit poor safety during interactions with marine organisms and artificial structures, resulting in limited environmental adaptability. Inspired by the locomotion mechanisms of aquatic creatures, underwater bionic soft robots, with deformable soft bodies featuring low flow disturbance and high collision tolerance, have attracted substantial research interest worldwide [1]. Most existing reviews focus on individual technologies and lack a systematic overview of technological evolution, cutting-edge developments, and technical bottlenecks [2]. Adopting a systematic

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literature review method, this paper analyzes representative domestic and international studies and prototypes published over the past decade, traces the historical evolution of the field, and outlines key technical systems including biomimetic structures, flexible actuation, as well as sensing and control modules [3]. It provides literature references and research insights for future optimization of robot structures, iteration of low-power flexible actuators and development of underwater adaptive motion-control systems.

2. Underwater bionic design and technological evolution

2.1. Classification of aquatic biological bionic prototypes (fish, jellyfish)

After long-term natural evolution, marine organisms have formed highly-efficient underwater locomotion modes, which provide abundant bionic references for soft-robot design. Current research on underwater bionic soft robots mainly focuses on two bionic objects: fish and jellyfish.

Fish generate propulsive force through Body-and-Caudal-Fin (BCF) mode or Median-and-Paired-Fin (MPF) mode. The BCF mode relies on coordinated oscillation of body and caudal fin to produce thrust, featuring high swimming speed and favorable propulsive efficiency, which is the primary imitated object for bionic fish. For example, carangiform fish achieve high-speed continuous swimming with stiff caudal fins cooperating with flexible bodies. The MPF mode obtains power via oscillation of paired fins such as pectoral fins. Although it cannot reach high speed, it possesses outstanding turning and maneuvering capacity, suitable for fine motion in narrow spaces. Most fish-inspired soft robots are fabricated from flexible silicone and elastic polymers. They replicate the continuous oscillatory motion of fish bodies and are mainly deployed for near-sea monitoring and water-sample collection missions.

Jellyfish obtain reaction force for locomotion by periodic contraction and expansion of their umbrella-shaped bodies to squeeze internal water. Jellyfish swim at low speed yet consume little energy, and own favorable vertical floating-diving capacity. Their bodies consist entirely of flexible gel-like tissues, a feature that closely matches the material properties required for soft-robot bodies. Bionic jellyfish prototypes are generally designed as umbrella-shaped flexible cavities, whose umbrella structures are driven by actuators to open and close periodically. Their prominent advantage lies in extremely low flow disturbance without startling surrounding marine organisms, so they are suitable for marine-organism observation. Besides fish and jellyfish, animals including crabs and manta rays have also been adopted as bionic templates for robot design, though far fewer prototypes have been developed based on these organisms.

Table 1. Performance comparison of typical bionic underwater softrobot prototypes

Prototype Type	Propulsion Mode	Swimming Speed	Maneuverability	Flow Disturbance	Typical Application
BCF-inspired fish	Body-caudal fin oscillation	High	Medium	Medium	Long-range near-sea survey
MPF-inspired fish	Pectoral/paired fin oscillation	Low-medium	Excellent	Medium	Narrow-space fine detection
Jellyfish-inspired robot	Umbrella cavity periodic contraction	Low	Poor	Very low	Marine organism silent observation

The selection of bionic prototypes directly determines robot configuration, actuation scheme and applicable scenarios. Fish-inspired prototypes tend to perform long-distance horizontal cruising; jellyfish-inspired ones are more suitable for low-speed vertical movement and silent observation. In practical prototype development,

researchers seldom completely copy biological structures. Instead, they extract core locomotion mechanisms and carry out simplified design combined with engineering conditions, balancing bionic fidelity and engineering feasibility [1]. Based on the above research, the authors conducted a performance comparison of typical bionic underwater soft robot prototypes; the results are shown in Table 1.

2.2. Stages of technological development and representative prototypes of each stage

The development history of underwater bionic soft robots can be roughly divided into three phases: the rigid bionic-prototype stage, preliminary soft-body realization stage and intelligent-upgrading stage.

The first phase is the rigid bionic-prototype stage (before 2010). Although robots in this phase imitated the appearance of aquatic creatures, their bodies were mainly made of rigid materials such as metal and hard plastic. Motions were driven by traditional mechanisms including motors and gears. These robots could reproduce general biological postures, but their bodies lacked flexible-deformation capability. Essentially, they belonged to rigid bionic robots. A representative example is MIT's Robotuna, an early multi-link rigid bionic fish. It achieved desirable locomotion performance but suffered poor collision safety and could hardly adapt to complex reef environments. Research in this phase focused on verifying bionic propulsion mechanisms, while flexible materials and flexible actuation had not become mainstream.

The second phase is the preliminary soft-body realization stage (2010-2018). With the development of flexible polymer materials and flexible-actuation technologies, researchers widely adopted silica gel to fabricate robot bodies, and genuine underwater soft robots emerged successively. Robot bodies could achieve continuous large deformation. Pneumatic actuation and Shape-Memory-Alloy (SMA) actuation were widely adopted. Typical prototypes consist of pneumatically actuated bionic jellyfish, whose flexible bells periodically expand and contract under air-pump actuation, as well as SMA-driven multi-degree-of-freedom bionic fish that rely on the thermal phase transition of SMA to produce body undulation [4]. Typical SMA bionic fish could realize oscillation frequency of 0.5-1.2 Hz and attain a swimming speed around 0.1 body-length per second. Most prototypes developed in this stage achieved basic bionic motions under open-loop control. Since they were typically powered by external tethers, their motion accuracy was limited, and functional validation could only be conducted in laboratory water tanks.

The third phase is the intelligent-upgrading stage (2018-present). Novel smart materials, miniature sensing units and embedded control algorithms are continuously integrated into prototype development. Besides traditional pneumatic and SMA actuation, novel actuation schemes such as magnetic-field actuation and Dielectric-Elastomer Actuation (DEA) are developing rapidly. Some prototypes integrate flexible sensors to realize motion-state feedback. Increasing untethered prototypes attempt offshore tests beyond water tanks. Typical cases include the DEA-driven bionic-crab robot CRAB-EDM, which proposes a timing-discharge strategy to handle residual-charge problems, achieving actuation frequency up to 7 Hz; magnetically-controlled micro bionic jellyfish achieve wireless non-contact driving via external magnetic fields. Research in this phase focuses on sensing-actuation integration, closed-loop control and adaptation to real-world underwater environments. Nevertheless, most prototypes still stay at laboratory-verification stage, and considerable gaps remain before large-scale engineering application.

3. Research status of underwater bionic soft robots

3.1. Research status of flexible-body structural design

Compared with traditional rigid underwater robots, underwater bionic soft robots possess multiple prominent advantages elaborated as follows. First of all, they deliver high safety in environmental interaction. Mainly

composed of flexible polymer materials, their bodies absorb impact energy through deformation during collisions. They will neither inflict physical damage on corals and marine organisms nor easily suffer structural failure themselves, making them ideal for reef and wildlife-habitat scenarios requiring high interaction safety. Secondly, they generate low water disturbance and noise. Unlike high-speed rotating propellers, which generate loud noise and substantial flow disturbance, soft robots achieve propulsion via continuous body deformation. Their low-disturbance and low-noise characteristics ensure they will not interfere with biological behaviors during marine-organism observation. Thirdly, they feature strong adaptability to complex-terrain environments. Deformable soft bodies can squeeze through narrow caves and reef gaps inaccessible to rigid robots, expanding the accessible scope of underwater operations. Fourthly, flexible-body structures are highly plastic. Tuning the proportions of constituent materials allows adjustment of body density to facilitate buoyancy control. However, flexible bodies also bring inherent drawbacks. Low stiffness of flexible materials limits their resistance against water-flow impact. Long-term immersion in seawater will cause swelling, corrosion and aging failure, raising higher requirements for structural design [5].

At present, flexible-body structural design mainly includes two technical routes: integral casting and modular assembly. Integral casting mostly adopts silica gel, producing complete soft bodies via mould casting. It brings good integrity and sealing performance, suitable for relatively simple prototypes such as small-size bionic fish and jellyfish. Its disadvantage lies in difficult structural modification after moulding. Modular assembly separately fabricates actuation units, flexible substrates and functional components before assembly. This approach enables convenient module replacement and maintenance and is widely adopted for multi-legged robotic prototypes. However, assembly gaps brought by modular splicing greatly increase underwater-sealing difficulty.

Silicone rubber is the most-widely-used material with favorable tensile performance and low cost. Yet ordinary silica gel has limited resistance against seawater corrosion and swelling. Some studies adopt composite flexible materials with internal fiber-constraint layers to restrain unexpected deformation and improve actuation efficiency [6].

3.2. Research on prototypes adapted to different water-depth scenarios (focus on shallow-sea, brief discussion on deep-sea)

At present, most underwater bionic soft-robot prototypes are tested in laboratory water tanks and shallow-sea environments within 0-50 m depth. Shallow-sea areas contain abundant coral-reef and coastal biological resources, corresponding to practical demands such as ecological monitoring and underwater-facility inspection. Meanwhile, relatively low hydrostatic pressure in shallow-sea puts forward moderate requirements for soft-body compression resistance, which is convenient for prototype sea trials. Numerous fish-inspired and jellyfish-inspired prototypes are developed for shallow-sea scenarios.

Nevertheless, shallow-sea environments also bring practical challenges. Near-shore waters suffer turbulent currents, waves and undercurrents. High-salinity seawater accelerates corrosion and aging of flexible materials. Suspended sediment and marine-organism fouling in seawater will interfere with normal operation of actuators and sensors. Most existing prototypes are tested under calm tank conditions, while test data under real-world shallow-sea flow conditions are relatively insufficient.

For deep-sea applications, harsh environmental factors such as high hydrostatic pressure and low temperature substantially alter the mechanical properties of flexible polymer materials and induce drift in the output characteristics of actuators. Deep-sea environments set extremely high standards for robot sealing, compression resistance and power supply. Restricted by material and hardware conditions, the quantity of deep-sea bionic soft-robot prototypes is small, and most stay at the principle-prototype stage. In recent years,

several research groups have completed principle verification of soft-driven prototypes under Mariana Trench-level 10,000-m deep-sea conditions, yet no mature practical deep-sea bionic soft-robot system is available [3]. Current deep-sea exploration tasks are still dominated by rigid ROVs and AUVs, and deep-sea soft robots represent a key future research direction.

4. Actuation and control of underwater bionic soft robots

Actuation systems serve as the "muscles" of underwater soft robots, determining locomotion speed, output force and response frequency, and constituting the core component of the whole system. Various actuation schemes are available for underwater bionic soft robots. This paper focuses on pneumatic actuation and SMA actuation, the two most-widely-adopted solutions, and briefly introduces hydraulic actuation and novel smart-material actuation.

As one type of fluid-driven approach, pneumatic actuation represents the earliest-developed and most-mature flexible-driving technology. Compressed gas is pumped into flexible chambers to generate expansion and bending deformation under pressure difference. Chambers restore initial shapes by material elasticity after gas release. Pneumatic actuation provides large output force and large deformation with simple control logic and low cost. Its prominent drawback is that external air pumps and pipelines are generally required, which makes untethered design difficult. Bulky pump systems are unfavorable for robot miniaturization. Most underwater pneumatically driven prototypes are confined by external pipelines and thus have a limited range of motion.

SMA actuation belongs to thermal actuation. SMA alloys produce considerable deformation through solid-state phase transition under specific temperature and recover original shapes after cooling. SMA wires are heated by electric power and cooled by surrounding water underwater. SMA-driven structures are highly compact without pipelines, which facilitates prototype miniaturization. Many small-scale prototypes of bionic fish and bionic jellyfish employ SMA as their driving units [7]. SMA has inherent drawbacks: heating-cooling cycles limit response speed and prevent high-frequency reciprocating motion. High power consumption and material fatigue fracture caused by repeated thermal cycles restrict service life.

Hydraulic actuation shares similar principles with pneumatic actuation, replacing gas with liquid to drive chambers. Incompressible liquid delivers larger output force and better control precision than pneumatic solutions. However, hydraulic systems are heavier and demand stricter sealing conditions, so their applications in underwater soft robots are less common than pneumatic counterparts. Actuation based on novel smart materials covers magnetic-field actuation and dielectric-elastomer actuation, among other techniques, and represents a future development direction for soft actuation. Magnetic-field-driven performance is limited by the working-space range of external magnetic coils. DEA requires kilovolt-level high voltage and faces tough underwater-insulation challenges, so most relevant research remains at laboratory stage.

Horizontal comparison among mainstream actuation approaches shows that pneumatic actuation delivers large force and deformation yet depends on external pipelines. SMA features a compact structure for miniaturization but suffers from slow response and material fatigue. Hydraulic actuation provides strong output force yet brings bulky systems. Magnetic-field actuation realizes wireless driving but only suits micro-scale prototypes. DEA achieves high power density and fast response yet encounters high-voltage-insulation difficulties. No single existing actuation can simultaneously satisfy large output force, high-frequency response and untethered miniaturization. Obvious performance trade-offs exist among various schemes, and researchers need to make trade-offs according to application scenarios [2].

In terms of motion control, a large number of underwater soft robots still adopt open-loop control, outputting driving signals according to preset time sequences without feedback of actual deformation and motion status. Open-loop control is easy to implement, yet motion accuracy will degrade obviously under water-flow disturbance and material-performance drift. When closed-loop control is adopted, soft robots behave as nonlinear systems characterized by large deformation and infinite degrees of freedom. Fluid-structure-interaction modelling is difficult and accurate dynamic models are hard to establish [8]. Some studies introduce flexible sensors to obtain body-deformation information and carry out closed-loop control combined with intelligent algorithms. Nevertheless, sensor corrosion and measurement drift under underwater interference remain unsolved problems [9].

5. Opportunities and challenges in this field

Ongoing advances in marine resource exploitation and marine ecological protection create substantial development opportunities for underwater bionic soft robots. Tasks such as reef-area ecological observation, marine-organism-behavior monitoring and narrow-space detection, which cannot be well completed by traditional rigid underwater robots, provide broad application scenarios for soft robots. Continuous iteration of flexible materials, smart actuation and embedded-sensing technologies also lays technical foundations for performance improvement of underwater bionic soft robots [10]. Meanwhile, multiple critical challenges remain to be addressed. It is worth emphasizing that these technical bottlenecks are not independent of one another but mutually coupled. For instance, seawater-induced material aging will shorten actuator service life and trigger sensor drift, which further degrades control precision.

The first challenge lies in material-performance bottlenecks. Existing flexible polymer materials are prone to swelling, corrosion and biological fouling in seawater. Long-term immersion changes material mechanical properties and accelerates actuator aging and failure. Flexible materials combining high tensile property, seawater-corrosion resistance and anti-aging performance are still insufficient.

The second challenge concerns practicalization of actuation systems. Each actuation type has inherent defects. Conflicts exist among high output force, high-frequency response, low power consumption and untethered miniaturization. Underwater sealing and insulation of driving units constitute tough engineering obstacles.

Thirdly, underwater sensing and closed-loop control face great difficulties. Large soft-body deformation brings difficulties to fluid-structure-interaction modelling. Underwater environments cause severe interference to flexible sensors, which makes it difficult to acquire stable and reliable sensing signals. Mature embedded closed-loop control solutions are still lacking [11].

Fourthly, low practicalization level of prototypes. Most prototypes can only complete verification in laboratory water tanks. Few prototypes work for long durations under real-world current and seawater-corrosion conditions. Insufficient endurance prevents prototypes from practical marine operations.

In the future, with continuous progress in material science, actuation technology and intelligent control algorithms, underwater bionic soft robots are expected to break existing technical shackles and play greater roles in marine-ecology observation and near-sea-exploration scenarios.

6. Conclusion

Through classification and comparison of representative prototypes, it is concluded that underwater bionic soft robots possess prominent advantages in collision safety, low flow disturbance and environmental adaptability, making them highly promising for shallow-sea ecological observation and narrow-space detection.

Nevertheless, this field still confronts major bottlenecks: seawater-triggered material aging, inherent drawbacks of available actuation strategies, challenges in fluid-structure interaction modelling and closed-loop control, and the low practical applicability of existing prototypes. Future research should prioritize the development of seawater-resistant composite flexible materials, hybrid actuation schemes that combine complementary driving mechanisms, and embedded adaptive control algorithms integrating flexible sensing. More long-duration sea trials under real marine conditions are also needed to bridge the gap between laboratory prototypes and practical engineering applications. It is expected that bionic soft robots will form complementary operation systems with conventional rigid underwater robots to jointly support marine resource exploitation and ecological conservation.

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